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A Thermal Infrared Technique for Monitoring Cotton Water Stress and Scheduling Irrigations

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ABSTRACT

STEPWISE, multiple linear regression analysis established that a crop water stress index (CWSI) derived from mid-day radiant leaf temperatures, air temperatures, and vapor pressure deficits was the most important independent variable in predicting the xylem pressure potential of cotton leaves. When the CWSI was combined with the age of the crop and the evaporative demand of the atmosphere, the water potential of cotton could be predicted throughout the entire growing season. This permits day by day monitoring of cotton plant water status which could facilitate the irrigation decision making progress without resorting to tedious physiological plant measurements.

INTRODUCTION

A quantitative estimate of impending plant water stress is a critical prerequisite for the efficient scheduling of irrigations. Ideally, the warning of stress should come from the crops themselves, obviating the need for precise information regarding available soil moisture, root distribution and evaporative demand of the atmosphere. Unfortunately, many of the methods for quantifying physiological plant stress are both labor intensive and tedious. Furthermore, they are subject to considerable experimental and sampling error (Ritchie and Hinckley, 1975). In fact, the variability between plants is often so large that it obscures any real differences which might otherwise be attributed to plant water status. Physiological approaches often involve measurements on single plants, leaves and petioles; as such they are point measurements, many of which may be required to characterize a field because of differences in soil properties. Examples include xylem pressure potential (Scholander et al. 1965), leaf diffusion resistance (Kanemasu, 1975) and petiole and leaf water contents (Longenecker and Lyerly, 1969). Although various indicators of this type have been suggested to schedule irrigations to achieve increased water use efficiency (Namken, 1965; Hiler and Clark, 1971; Hiler et al. 1974; Misra and Pant, 1981), economic considerations will probably limit their widespread acceptance (Stegman et al. 1976).

The relationship between plant leaf temperatures and moisture stress has been qualitatively documented for a number of years (Wiegand and Namken, 1966; Ehrler, 1972; Jackson in press), and evidence is now accumulating which establishes infrared (IR) thermometry as a reliable surrogate for certain physiologically-based water stress measurements. Ehrler et al. (1978) showed an inverse relationship between the stress degree day parameter [i.e., SDD = canopy temperature (T_c) minus air temperature (T_a)] and the xylem pressure potential (ψ_ℓ) of wheat. Later, Idso et al. (1981a) refined the SDD by taking the evaporative demand of the atmosphere into account. The transformed stress parameter which is termed the crop water stress index (CWSI) was well correlated with ψ_ℓ in alfalfa plants subjected to varying degrees of water stress (Idso et al. 1981b). The major advantage which IR thermometry offers over conventional stress assessment techniques is the ease and rapidity with which plant temperature measurements can be made (Pinter, 1982; Jackson, 1982). Since entire fields can be surveyed in a short period of time, this technique appears to offer potential for scheduling irrigations on a cost effective basis (Jackson et al. 1980; Geiser et al., 1982).

The objectives of the research reported here are threefold: first, to establish a relationship between the CWSI and the ψ_ℓ of cotton leaves; second, to examine this relationship throughout the season for differentially-irrigated cotton plots and; third, to determine its potential utility for scheduling irrigations.

EXPERIMENTAL METHODS

The cotton experiment* was conducted during 1980 in a 2-ha field located on the University of Arizona, Cotton Research Center Farm in Phoenix, AZ. The soil is an Avondale Loam [a fine loamy, mixed (calcareous), hyperthermic, Anthropic Torrifluvent]. Short staple cotton *(Gossypium hirsutum* L. var. 'Deltapine-70') was planted in E-W oriented rows on 14 April 1980 and then thinned to a stand density of 86,000 plants/ha. Briefly the experiment consisted of six replications of six different early season irrigation treatments. The final irrigation was applied in mid-August. Two replications of each treatment were used for the data reported here.

Cotton leaf xylem pressure potentials were measured with a pressure bomb apparatus using techniques similar to those proposed by Scholander et al. (1965). Measurements were taken at irregular intervals during the season, but mainly on the day before an irrigation, then once again 2 to 3 days following irrigation. Three sunlit leaves (at the 4th node from the top) were selected and cut from each field plot. They were immediately placed in plastic bags and stored in a moist insulated chest: measurements were made within 45 min of field collection. Determinations were made from 1200 to 1500 h (MST), an interval during which cotton ψ_ℓ remains relatively constant (R. Reginato and S. Farah, unpublished data).

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Radiant leaf and canopy temperatures were obtained between 1330 and 1345 h (MST) using a portable hand-held infrared thermometer (10.5 to 12.5 μm bandpass filter, 4° FOV) that was calibrated for use in high ambient air temperatures. Average leaf temperatures (T_ℓ) were obtained by aiming the IR thermometer at eight individual expanded leaves selected at random from the top of the canopy. Average canopy temperatures (T_c) were taken with the radiometer pointed obliquely towards the crop (about 15 to 25 deg from the horizontal) and at right angles to the row direction (4 viewing north and 4 viewing south). It is important to make the distinction between T_ℓ and T_c. The former represents temperatures of plant parts only while the latter may include a composite of plant and background soil temperatures.

No corrections were made in the apparent temperatures for leaf or canopy emissivities; nor was the radiant flux from the sky considered in making the temperature observations. Neglecting these parameters introduces a variable 1 to 1.5 °C negative bias in the absolute temperatures, however, they can be ignored when the primary concern is the relative differences which exist between treatments or day to day changes within a single treatment (Perrier, 1971). At the start and finish of each set of IR measurements, wet and dry bulb temperature measurements were made in the field with an aspirated psychrometer held at a height of 1.5 m above the soil. Solar radiation was measured with a hemispherical pyranometer.

RESULTS AND DISCUSSION

Calculation of the CWSI

To determine whether IR thermometry would provide a reliable method for following changes in cotton plant water status from one irrigation to the next, the T_ℓ data were transformed into the CWSI parameter proposed by Idso et al. (1981a). First, it was necessary to establish expected leaf temperatures for non-stressed plants as a function of air temperature (T_a, °C) and vapor pressure deficit (VPD, kPa). Accordingly, we selected a subset of T_ℓ data consisting of temperatures obtained on clear days when the treatments were assumed to be non-stressed (i.e., 3 to 8 days following an irrigation). The differences between T_ℓ and T_a (i.e., the SDD) were linearly correlated with VPD (Fig. 1). The resulting baseline was described by the linear relation

$$\mathrm{SDD} = 1.71 - 1.90\,(\mathrm{VPD}) \quad [1]$$

$r^2 = 0.45 \quad n = 133$

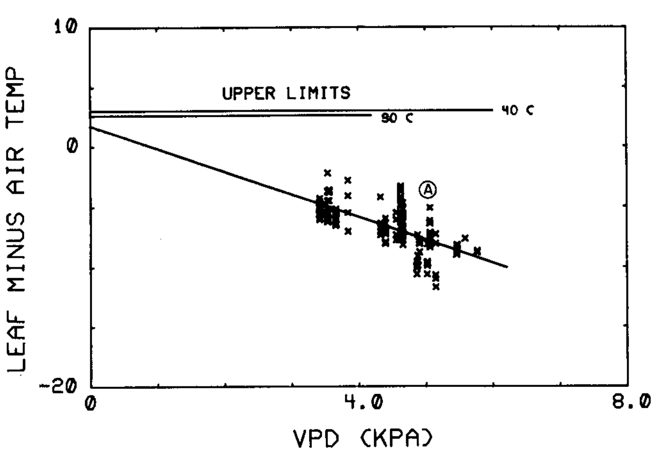

FIG. 1 T_ℓ minus T_a as a function of vapor pressure deficit for non-stressed cotton plants. Horizontal lines show theoretical upper limits for plants which are stressed so severely that transpiration has ceased.

The data show that non-stressed cotton maintains apparent leaf temperatures 5 to 10 °C cooler than air temperatures under ambient vapor pressure deficits normally encountered during Arizona summer conditions. When water in the effective rooting zone of the crop becomes limiting, leaf temperatures rise above this baseline because transpirational cooling is reduced. In fact, we interpret the scatter of data points about the baseline in Fig. 1 as an indication that at times the plants in certain plots might not have been transpiring at a potential rate. This does not, however, diminish the utility of the baseline as a reference point for comparison purposes. When transpiration ceases altogether, $T_\ell - T_a$ attains an upper limit which is specified by radiant and convective energy exchanges. Idso et al. (1981a) indicated that the upper limit varies with ambient temperatures, and that for practical purposes it can be approximated by an empirically-based algorithm which takes the vapor pressure gradient between T_ℓ and T_a (at VPD = 0) into account. Note that even when the air is saturated, leaf temperatures which are warmer than air temperatures enable a vapor pressure gradient to persist. As an example, upper limits for a severely stressed, non-transpiring crop are shown on Fig. 1 for T_a of 30 to 40 °C.

The CWSI is defined within the context of the range over which T_ℓ can vary due to water stress conditions. It is the ratio of the deviation of the measured $T_\ell - T_a$ from the well watered baseline to the complete range for a given VPD. The CWSI is dimensionless and in theory should progress from 0 for non-stressed plants transpiring at potential rates to 1 for severely stressed plants which are not transpiring. In this experiment with cotton we found the CWSI exceeded the expected limits, varying from −0.5 to +1.5 due mainly to the variability around the baseline and to a lesser degree the empirical method by which the upper limit is determined.

As an example of how the CWSI is calculated, consider point A in Fig. 1. This value represents a measured leaf temperature of 37 °C at T_a = 40 °C and VPD of 5.0 kPa. If the plant had sufficient water to transpire at the potential rate, we calculate from equation [1] that $T_\ell - T_a$ should have been −7.8 °C. Conversely, a severely stressed crop would be expected to be 3 °C warmer than the air. The total range over which $T_\ell - T_a$ could vary due to water stress would be +3 °C − (−7.8 °C) or 10.8 °C. Since the measured $T_\ell - T_a$ was −3 °C, the plants were 4.8 °C above the expected baseline and the CWSI is 4.8/10.8 = .44.

Trends in CWSI

The season long trend of CWSI (based on T_ℓ) is shown for two representative treatments in Fig. 2. The CWSI follows a cyclical pattern which is synchronous with the irrigation events (indicated by arrows along the upper margins). Almost immediately following an irrigation the CWSI falls to a minimum value and then climbs slowly as the crop exhausts its supply of water. The rate of increase in CWSI between irrigations is directly related to the evaporative demand of the atmosphere and the physical size of the plants (i.e., their demand) and inversely related to the availability of water stored in the

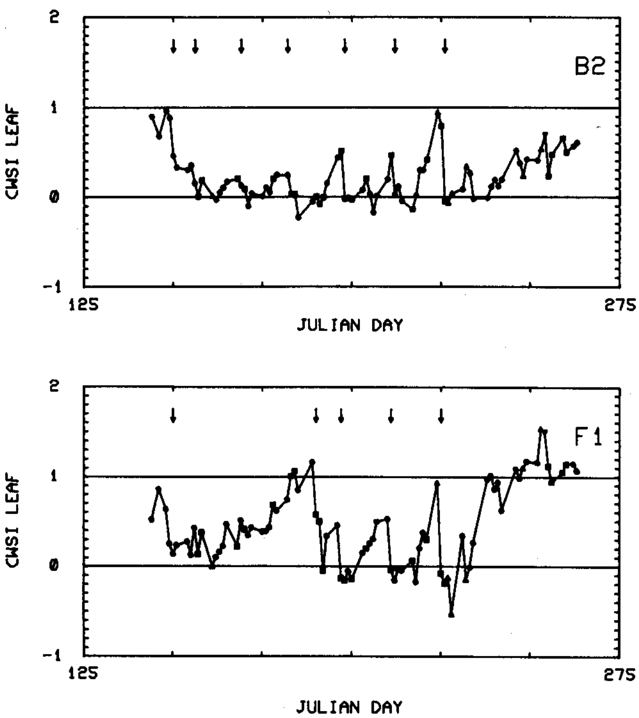

FIG. 2 Seasonal trend of $CWSI_{leaf}$ for two early season cotton irrigation treatments. Arrows along upper axis represent irrigation events.

soil. Note that the CWSI does not return to zero following irrigations early in the season. We do not interpret that to mean that the irrigations were not adequate. Rather, it appears that leaf temperatures of smaller plants are more closely coupled to their thermal radiant environment than those of larger plants. As a consequence, it may be that non-stressed plants will require a different baseline early in the season.

Comparison of CWSI with Leaf Xylem Potential

The ψ_ℓ data for all treatments were paired with corresponding daily values of CWSI and analyzed by conventional polynomial regression techniques. Residual analysis indicated that although these two variables were very well correlated from mid-June until mid-August, prior to that time the CWSI predicted a more negative ψ_ℓ than was found. After mid-August the reverse was true. To determine which additional environmental and crop factors were most important in determining ψ_ℓ and to compensate for this seasonal effect, stepwise multiple linear regression analysis was employed (Table 1). Leaf xylem pressure potential was designated as the dependent variable; the independent variables were the age of the crop, air temperature at 1.5 m, vapor pressure deficit, solar radiation, and CWSI based on both T_ℓ and T_c.

Correlations Between Variables

Partial correlations between the variables are summarized in Table 2. Leaf xylem pressure potential was most highly correlated with CWSI leaf and also with the age of the crop. Note that the correlation between CWSI canopy and ψ_ℓ was not highly significant. This was due to the influence of varying amounts of soil viewed by the IR thermometer early in the season when the plants were small and also later in the season when lodging opened several of the canopies. A significant partial correlation between variables does not necessarily imply a cause-effect relationship (viz. solar radiation and crop age), however, the absence of significance suggests that the variables are independent of one another. An important finding was that CWSI leaf was not correlated with air temperature, vapor pressure deficit or solar radiation. Leaf xylem pressure potential also appeared independent of VPD if only partial correlations are considered. But as

TABLE 1. VARIABLES TESTED IN THE STEPWISE MULTIPLE REGRESSION PROCEDURE.

Variable	Symbol	Status	Units	Range	Mean	SD
Leaf xylem pressure potential	ψ_ℓ	dependent	MPascals	−1.58 to −3.55	−2.54	0.54
Age of crop	Age	independent	days from planting	43 to 132	111	31.9
Air temperature (+1.5 m)	T_a	"	°C	29.5 to 40.9	36.0	2.83
Vapor pressure Deficit (+1.5 m)	VPD	"	kPascals	2.11 to 6.71	4.48	1.06
Solar Radiation	I	"	W m^{-2}	757 to 999	886	46.1
CWSI leaf	$CWSI_\ell$	"	dimensionless	−0.33 to +1.15	+0.37	0.34
CWSI canopy	$CWSI_c$	"	dimensionless	−0.50 to +3.05	+0.52	0.62

TABLE 2. MATRIX OF PARTIAL CORRELATIONS BETWEEN VARIABLES LISTED IN TABLE 1 (n = 147).

	ψ_ℓ	Age	T_a	VPD	I	$CWSI_\ell$	$CWSI_c$
ψ_ℓ	1.000	−0.548**	−0.135	−0.139	−0.203*	−0.672**	−0.176*
Age		1.000	−0.220**	−0.387**	−0.673**	0.176*	−0.419**
T_a			1.000	0.868**	0.590**	−0.090	−0.188*
VPD				1.000	0.630**	0.003	0.145
I					1.000	−0.045	0.174*
$CWSI_\ell$						1.000	0.568**
$CWSI_c$							1.000

*Significant partial correlation at $0.05 > P > 0.01$.
**Significant partial correlation at $P < 0.01$.

TABLE 3. SUMMARY OF STEPWISE MULTIPLE LINEAR REGRESSION RELATING THE XYLEM POTENTIAL (ψ_ℓ) OF COTTON LEAVES AT 1200-1500 H (MST) TO PLANT AND ENVIRONMENTAL PARAMETERS. DATA WERE BASED ON 147 OBSERVATIONS OF MEAN ψ_ℓ THROUGHOUT THE SEASON.

Step	Added Variable	Predictive Equation	r^2	SE of Predicted ψ_ℓ (MPa)
1	$CWSI_{leaf}$	$\psi_\ell = -2.144 - 1.073$ (CWSI)	0.45	0.398
2	Age of Crop	$\psi_\ell = -1.364 - 0.948$ (CWSI) $- 0.007$ (Age)	0.64	0.323
3	VPD (kPa)	$\psi_\ell = -0.274 - 0.905$ (CWSI) $- 0.010$ (Age) -0.19 (VPD)	0.76	0.269

will be shown in the next section, VPD does exert a second order modifying effect on ψ_ℓ once the primary effects of water stress have been removed.

Multiple Linear Regression

The stepwise regression procedure established that the CWSI based on T_ℓ, T_a and VPD explained 45 percent of the variability in ψ_ℓ (Table 3). Subsequent inclusion of the age of the crop and VPD improved the prediction of ψ_ℓ significantly. It is believed that the age of the crop reflects physiological or morphological changes in plant response which were not measured (i.e., osmotic potential, leaf diffusion resistance, leaf thickness, etc.). The fact that VPD improved the estimate was not totally unexpected. Even though the CWSI is normalized to account for VPD, it probably also exerts a direct effect on ψ_ℓ, as shown for alfalfa by Idso et al. (1981b). The final equation for predicting ψ_ℓ of cotton was

$$\psi_\ell = -0.274 - 0.905(\text{CWSI}) - 0.010(\text{age}) - 0.19(\text{VPD}) \quad \ldots\ldots [2]$$

$r^2 = 0.76 \quad n = 147$

where ψ_ℓ is in MPascals, CWSI is based on apparent T_ℓ, the age of the crop is in days from planting and VPD is in kPascals. Fig. 3 shows good correspondence between observed ψ_ℓ and that predicted using equation [2]. The standard error associated with prediction was 0.269 MPa. The regression analysis showed that the addition of air temperatures, solar radiation or CWSI canopy as independent variables did not improve the estimate significantly.

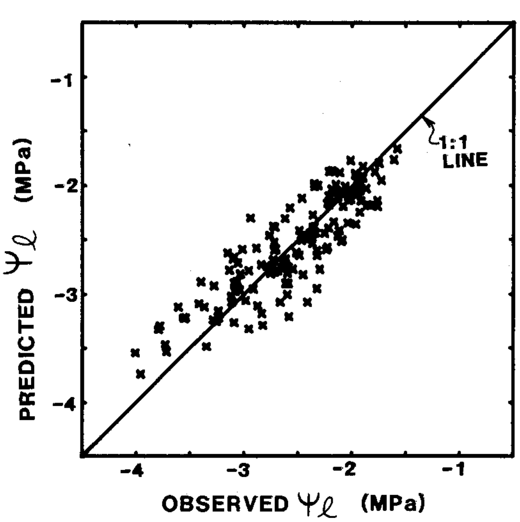

FIG. 3 A comparison of predicted and observed cotton leaf water potentials.

Trends in Predicted ψ_ℓ

Equation [2] was used in a predictive mode to calculate the ψ_ℓ throughout the season for all days when the CWSI measurements were obtained. Fig. 4 shows the results for the same two treatments portrayed earlier and permits the data to be visualized in a more conventional stress format for the entire season, even though actual ψ_ℓ measurements were only available for a relatively few days for each treatment. Actual ψ_ℓ measurements are shown as circles while the predicted values are shown as a continuous line in Fig. 4.

Good correspondence between the actual and predicted data points was expected, since the former were used to generate the model. The important concept which Fig. 4 illustrates is that predicted ψ_ℓ values are highest (least negative) after irrigation and decline in a regular fashion between irrigations. Some day to day variability is present in the data but the trends between irrigations are clear and could be projected to permit advance decisions for timing the next irrigation. In the case of plot F1 (bottom graph of Fig. 4) it is clear that the second irrigation was delayed far beyond a ψ_ℓ which might

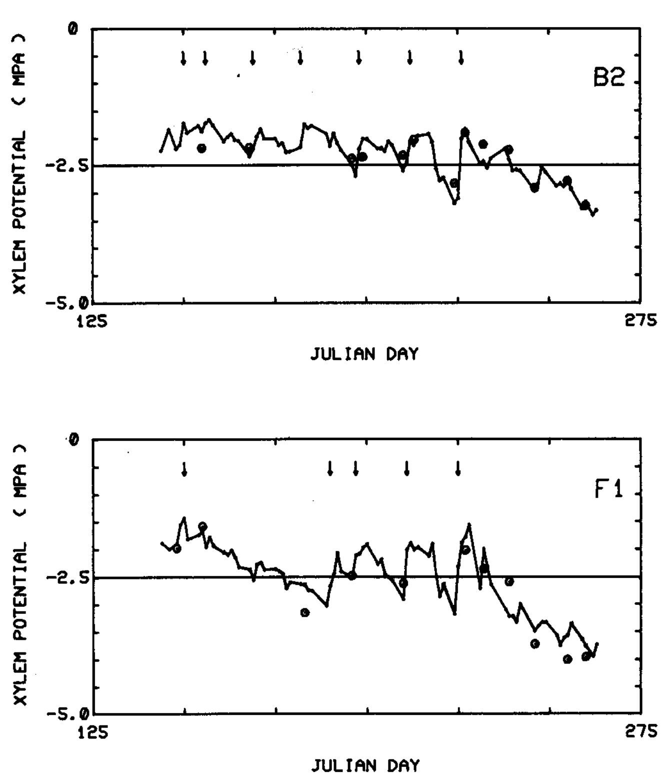

FIG. 4 Seasonal trends of predicted leaf xylem pressure potential (solid line) and actual measurements (circles) for two early season cotton irrigation treatments. Irrigation events are represented by arrows.

have signalled that the plant was severely stressed. However, we wish to point out that a given value of ψ_ℓ may not be the best single criterion on which to base irrigation scheduling decisions. This conclusion arises from the observation that ψ_ℓ is dependent on the ambient VPD. Equation [2] shows that ψ_ℓ decreases 0.2 MPA for a 1 kPa increase in VPD. Idso et al. (1981b) have shown ψ_ℓ changes of a similar magnitude for well-watered alfalfa and wheat, and more recently for cotton also (Idso et al., unpublished data). In fact the diurnal swing in VPD explains much of the variability associated with the dawn to midday decline in ψ_ℓ seen in those plants. If, however, one were to establish a minimum acceptable ψ_ℓ say −2.5 MPa, for signaling the need for irrigation, then equation [2] could be inverted to yield a corresponding maximum permissible CWSI. In this way IR thermometry could provide a rapid remote sensing means to schedule irrigations without resorting to the tedious and time consuming pressure bomb technique.

CONCLUSIONS

In summary, we have shown that a good correlation exists between the crop water stress index (CWSI) and an accepted physiological measure of moisture stress in cotton plants, the xylem pressure potential of leaves (ψ_ℓ). Although criteria for irrigating cotton in these experiments were based on preselected calendar dates, it is not difficult to visualize how predicted ψ_ℓ data, generated from easily acquired radiant leaf temperatures, air temperatures and vapor pressure deficits could be used to schedule water applications. A logical extension of this research is to bypass the traditional physiological measures of plant stress altogether and establish a maximum CWSI value which is consistent with optimum production under cost effective irrigation practices.

References

1 Ehrler, W. L. 1973. Cotton leaf temperatures as related to soil water depletion and meteorological factors. Agron. J. 65:404-409.

2 Ehrler, W. L., S. B. Idso, R. D. Jackson, and R. J. Reginato. 1978. Wheat canopy temperature: Relation to plant water potential. Agron. J. 70:251-256.

3 Geiser, K. M., D. C. Slack, E. R. Allred, and K. W. Stange. 1982. Irrigation scheduling using crop canopy — air temperature differences. TRANSACTIONS of the ASAE 25(3):689-694.

4 Hiler, E. A. and R. N. Clark. 1971. Stress day index to characterize effects of water stress on crop yields. TRANSACTIONS of the ASAE 14(4):757-761.

5 Hiler, E. A., T. A. Howell, R. B. Lewis, and R. P. Boos. 1974. Irrigation timing by the stress day index method. TRANSACTIONS of the ASAE 17(3):393-398.

6 Idso, S. B., R. D. Jackson, P. J. Pinter, Jr., R. J. Reginato, and J .L. Hatfield. 1981a. Normalizing the stress-degree-day parameter for environmental variability. Agric. Meteor. 24:45-55.

7 Idso, S. B., R. J. Reginato, D. C. Reicosky, and J. L. Hatfield. 1981b. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. Agron. J. 73:826-830.

8 Jackson, R. D., V. V. Salomonson, and T. J. Schmugge. 1980. Irrigation management — future techniques. p. 197-212. In: Proceedings of the Second National Irrigation Symposium of the ASAE, Lincoln, NB. 20-23 October 1980.

9 Jackson, R. D. 1982. Canopy temperatures and crop water stress. In: Advances in irrigation. Vol I, D. Hillel (ed.), Academic Press, NY, p. 43-85.

10 Kanemasu, E. T. (ed.). 1975. Measurement of stomatal aperature and diffusive resistance. Wash. State Univ. Bull. 809, Pullman. pp. 39.

11 Longenecker, D. E. and P. J. Lyerly. 1969. Moisture content of cotton leaves and petioles as related to environmental moisture stress. Agron. J. 61:687-690.

12 Namken, L. N. 1965. Relative turgidity technique for scheduling cotton *(Gossypium hirsutum)* irrigation. Agron. J. 57:38-41.

13 Misra, R. D. and P. C. Pant. 1981. Criteria for scheduling the irrigation of wheat. Expl. Agric. 17:157-162.

14 Perrier, A. 1971. Leaf temperature measurement. p. 632-671. In: Plant photosynthetic production manual of methods. Z. Sestak, J. Catsky and P. Jarvis (eds.). Dr. W. Junk, N.V. Publishers, The Hague.

15 Pinter, P. J., Jr. 1982. Remote sensing of microclimatic stress. p. 101-145. In: Biometeorology in integrated pest management. J. L. Hatfield and I. J. Thomason (eds.), Academic Press.

16 Ritchie, G. A. and T. M. Hinckley. 1975. The pressure chamber as an instrument for ecological research. p. 165-254. In: Advances in ecological research. A. MacFadyen (ed.), Academic Press, London.

17 Scholander, P. F., H. T. Hammel, E. D. Bradstreet, and E. A. Hemmingsen. 1965. Sap pressure in vascular plants. Science 148:339-346.

18 Stegman, E. C., L. H. Schiele, and A. Bauer. 1976. Plant water stress criteria for irrigation scheduling. TRANSACTIONS of the ASAE 19(5):850-855.

19 Wiegand, C. L. and L. N. Namken. 1966. Influences of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. Agron. J. 58:582-586.